REFLECTIONS ON MATERIALS AND METHODS FOR LATRINE PIT DESIGN

Key Findings and Recommendations

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Cover photo credit: Paul Kimera, Stacked Stone Pit Lining in Uganda

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ACRONYMS AND ABBREVIATIONS

ACCES	USAID Assainissement – Changement de Comportement et Eau pour le Sénégal
KII	Key Informant Interview
ODF	Open Defecation Free
RQ	Research Questions
SMSS	Safely Managed Sanitation Services
SSB	Stabilized Soil Block
UNICEF	United Nations Children's Fund
US	United States
USAID	United States Agency for International Development
USD	United States Dollar
USHA	USAID Uganda Sanitation for Health Activity
WASH	Water, Sanitation, and Hygiene
WASHPaLS	Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability

EXECUTIVE SUMMARY

Pit latrines, a common form of on-site sanitation in low-income settings, can collapse in areas with unstable soils, in flood-prone areas, or when they contain excess moisture. Pit collapse poses not only a safety concern for users, but also results in a sunk cost to consumers. Collapsed pits may ultimately lead households to abandon their pit latrines and revert to open defecation. Pit lining can provide structural support to prevent collapse and ensure longevity and ultimate sustainability, but existing pit lining options are often unaffordable and face challenges with marketability; published examples of alternatives are sparse. Despite a growing focus on product design and market development for latrine products such as slabs and superstructures, innovation around affordable, effective, and marketable pit lining materials and methods has been limited. At the request of the United States Agency for International Development (USAID), the Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) #2 activity conducted a two-phase study to examine existing options and potential innovations for pit lining (Phase 1), and propose an approach to sourcing, developing, testing, and examining select marketable innovations to improve pit lining options (Phase 2). This report highlights findings and recommendations from Phase 1.

Pit lining is needed in many cases: where there are wet pits, where pits are built in unstable soils, where there is flooding, or when emptying is required. Pit lining needs and considerations vary from country to country, region to region, and site to site. When linings are improperly constructed or designed, they may increase the risk of pit collapse, inhibit pathogen destruction, and cause pits to fill quickly. Linings necessarily reduce contact between pit contents and the surrounding soil, limiting in situ treatment. Thus, linings should be perforated whenever possible to ensure effluent can leach out. Sealed pit linings may cause premature filling of the pit and increase associated emptying needs, thereby increasing costs to households and public health risks in areas without access to safe emptying services.

Additionally, there is limited understanding of key concepts, techniques, and lining options among implementers and authorities. Limited knowledge among implementers and masons/builders can result in ineffective pit linings and/or poor construction quality. Limited knowledge among authorities can result in a lack of or overly restrictive regulation that limits innovation in materials and construction methods.

Common lining materials such as bricks and concrete are prohibitively expensive in rural sub-Saharan Africa, but some alternatives and options were identified that may be more affordable. Modifications to concrete mixtures, thicknesses, and porosity have been implemented with varying levels of success. Material combinations such as ferrocement and wire mesh can reduce the volume of concrete needed, reducing material costs. Further, biopolymers, natural resins, and cement may improve the strength of unstable soils and reduce lining material quantities or eliminate the need for lining altogether. Natural resins may also be able to increase the durability and longevity of widely-available materials such as bamboo when used for lining. Sandbags are widely available in many contexts and worth exploring outside their common uses in humanitarian settings. Additionally, several lightweight yet durable alternatives may be able to address affordability and transport challenges in some contexts, but need additional market testing and proof of concept. These include lightweight plastic linings and recycled plastic bricks. Affordable and widely-available materials may improve durability and ease of construction at minimal cost, including rebar reinforced fabric or wire mesh to hold stacked rocks in place.

Recommendations surfacing from this work include field testing and marketing pit lining applications and marketability of alternative lightweight and perforated concrete liners, plastic liners, and a range of new (combinations of) materials. The latter include concrete cloth, ferrocement and chicken wire, and cement reinforced stabilized soil linings as alternatives to concrete liners; natural resins, biopolymers and other stabilizers with potential to increase soil stability and reduce the need for lining; stackable alternatives to bricks such as plastic eco-bricks; and materials such as gabion or sandbags that can ease use and provide structure to locally found natural materials and excavated pit materials.

1.0 BACKGROUND AND PURPOSE

While the share of the global population with access to safely managed sanitation has continued to increase from 1990 to present, achievements are far below the targets set by global development goals. Approximately half of the world's population still lack access to improved sanitation (WHO/UNICEF 2021). Pit latrines, the most common on-site technology used across south Asia and sub-Saharan Africa, can qualify as a basic or even safely managed sanitation service under certain conditions, particularly when designed, constructed, and managed well.[1] Pits can function without water added (dry toilet) or with a water seal/flushing mechanism (wet toilet). An estimated 1.77 billion people in 2013 used a pit latrine as their primary means of sanitation, including facilities classified as improved (pour flush and push flush water-seal toilets, ventilated improved latrines, and pit latrines with slabs) and unimproved (traditional latrines and pit latrines without slabs) that may or may not be shared (WHO/UNICEF 2013).

However, pit latrines can often be unimproved, or run the risk of reverting from basic to unimproved, particularly when they are improperly designed and constructed. Pit collapse poses a real risk, particularly in areas with unfavorable soil conditions and/or high groundwater tables, when dry pits contain too much moisture, and when faced with heavy rains or floods. Pit collapse poses a direct danger to users of the facility and may result in households reverting to open defecation and the community's loss of open defecation free (ODF) status and benefits. Collapsed pits, along with the slab and superstructure, are often abandoned due to the risks and challenges associated with their repair and rehabilitation. This poses a significant welfare loss to impoverished households who had made the choice to invest in sanitation. There have been minimal efforts to date to quantify the extent of pit collapse, the reasons behind its occurrence, and associated challenges across contexts.

The risk of pit collapse is commonly addressed by constructing round pits, which are more structurally stable than square/rectangular pits; by reducing the pit dimensions, including both diameter and depth; and through pit lining. Pit linings provide structural integrity to reduce the risk of collapse; however, high-quality, durable, marketable, affordable, and acceptable options for pit linings are currently limited in many contexts, and existing materials options may inhibit latrine pit effectiveness. The water, sanitation, and hygiene (WASH) sector has likely over-relied on concrete and bricks for pit lining. Materials such as bricks, cement, wood, and aggregate can account for up to 80 percent or more of the up-front capital cost of latrine construction, with costs being particularly high in sub-Saharan Africa (Ulrich et al. 2016). Affordability of latrines is one of the largest barriers to purchase and access.

The total cost of digging and lining a pit can be anywhere from one-third to one-half of the total capital cost of a latrine, with the highest prices seen in sub-Saharan Africa. In 2016, the cost of a simple ventilated improved pit latrine with a 3-meter-deep pit in Uganda could cost between United States dollar (USD) 400 (unlined pit) to USD 800 (lined pit), with brick lining doubling the cost of the latrine compared to an unlined pit. In Bangladesh, however, the cost for a pan, slab, and concrete rings was less than USD 100 due to ready availability of components through thousands of small private sellers. Overall, cost data from 1 dry toilet examined in Uganda, 3 in Tanzania, and 1 in Kenya showed an average cost of USD 423 (ranging from USD 172 to USD 783). Cost data from 3 dry toilets examined in Nepal, 1 in India, and 1 in Nepal showed an average cost of USD 141 (ranging from USD 40 to USD 280) (Ulrich et al. 2016). Lining a pit significantly increases the cost of pit latrine construction, and these cost differences are particularly notable in sub-Saharan Africa.

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[1] Safely managed sanitation services (SMSS) are defined as the use of at least a basic sanitation facility and a handwashing facility with soap and water, which is not shared with other households, and where excreta are treated safely either on-site or off-site. For more details on definitions and how to monitor SMSS, visit [Monitoring Safely Managed On-Site Sanitation | JMP (washdata.org)](washdata.org).

While the price of cement has been slowly falling in sub-Saharan Africa, it is still far higher than in most of the Asia region[2] (Leone, Macchiavello, and Reed 2021). Recently however, there has been a global increase in cement prices due to rising energy and transport costs and widespread inflation (Adiguzel 2024). The quality of cement used is another challenge in many contexts. The cement industry in sub-Saharan Africa is rapidly growing, but it faces challenges related to industry standardization and quality control (Schmidt et al. 2018), often resulting in the use of sub-standard raw materials such as poor-quality sands, soils, and aggregates. Poor-quality cement further contributes to collapse when used for linings, slabs, and collars.

Transport costs can also be a significant driver of total latrine costs, particularly for remote areas, often adding 5–7 percent or more to the total up-front capital cost. Materials mentioned above, such as bricks, cement, wood, and aggregate, are very heavy, increasing transport challenges and associated costs when manufactured off-site. Difficult terrain, poor quality or nonexistent roads, and distance from markets can significantly increase the cost of materials and labor involved with purchase and delivery. Local skilled labor to construct a latrine is also often unavailable in the most remote locations and must be sourced from elsewhere, increasing labor costs (O'Reilly et al. 2017).

Wet- or dry-usage habits, soil conditions, moisture levels, available materials, location of and transport to the site, and other key conditions must be considered when designing and implementing latrine pit linings. The materials and the methods used for their construction and installation need to be fit-for-purpose and sensitive of the local context. However, details on latrine design, ideal operating conditions, and related information are often not available to the consumers and masons/artisans involved in the choice and construction of pit lining. Published examples of fit-for-context pit lining materials and methods are sparse, resulting in a dearth of promising options to increase durability of the latrine and reduce costs to consumers. Whether tailored specifically to individual local contexts or robust enough to address challenges across geographies and operating conditions, innovation is needed in this space.

An increased focus on pit lining innovation can both benefit from and further strengthen the sector focus on market-based sanitation (MBS). While there has been increased focus on making markets work, affordability of toilets and toilet products remains a key challenge. Most innovation, product design, and supply chain strengthening has focused on superstructures and toilet interface products like slabs and pans to identify low-cost materials or construction methods, and to bring down transport costs or increase ease of transport, installment, use, cleanliness, and durability. Pit lining, however, has largely been ignored despite innovative building techniques and materials emerging in construction and material engineering in recent decades that warrant exploration for their applicability and marketability for pit lining.

At the request of the United States Agency for International Development (USAID), the Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) #2 activity conducted a two-phase study to examine existing options and potential innovations for pit lining (Phase 1), and propose an approach to sourcing, developing, testing, and examining marketability of select innovations to improve pit lining options (Phase 2). This report presents the findings of Phase 1 and focuses on solutions with potential to address common challenges regarding marketability and durability of pit lining across contexts. The report presents the research questions guiding this work and data sources used to address them, then presents findings that highlight considerations for when lining is needed, the impacts of pit lining on latrine effectiveness and durability, and an overview of materials and methods with proof of concept and/or potential for pit lining applications and marketability. The report then briefly discusses reflections and key knowledge gaps, followed by targeted recommendations.

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2 In 2017 prices, one metric ton of cement ranged from USD 50–250 across sub-Saharan Africa. In most of Asia, by contrast, cement prices rarely exceeded USD 100 for the same quantity.

2.0 METHODOLOGY

2.1 RESEARCH QUESTIONS

Three Research Questions (RQ) guided the study:

RQ1. What are the implementation lessons learned from and costs of latrine pit lining materials and technologies employed across target geographies and population segments?

RQ2. What promising innovations in latrine pit design have potential to address common technical, operational, and contextual challenges; reduce costs; and achieve consumer uptake and scale?

RQ3. How can WASHPaLS #2 partner with and support promising innovations to test and/or improve their affordability, marketability, durability, scalability, and sustainability?

The RQs were addressed through a two-phased approach. Phase 1 consisted of a desk review and key informant interviews (KIIs) to compile data and information for existing, commonly used pit lining solutions and promising innovative, alternative options. This process was used to address RQ1 and RQ2. Results were compiled by country and region (where possible), with experiences documented throughout the desk review and interview process. Key stakeholder inputs from interviews helped to iteratively refine the framework for analysis and additional desk review. RQ3 will be addressed separately in Phase 2, which is forthcoming.

2.2 DATA COLLECTION

Academic and gray literature was reviewed and KIIs conducted to compile data on local solutions and innovations in pit lining that address common challenges, particularly focused on reducing cost while maintaining or improving structural integrity. A list of marketability and effectiveness criteria was developed iteratively with stakeholders to guide the identification of options and innovations. Effectiveness refers to the successful functioning of the pit lining itself, preventing collapse and ensuring effective containment and pathogen neutralization. Marketability refers to the external criteria that drive decision-making on latrine pit lining selection and installation, focused on latrine owners and masons/builders and their experiences, and broader factors such as supply chain considerations, regulation, and environmental and durability considerations. These criteria guided the review of materials and methods employed for lining across a wide range of contexts.

Marketability criteria for latrine pit design methods and materials include:

- *Availability and applicability* (i.e., materials and knowledge to install are within reach of latrine owners/users. Considerations include material sourcing, manufacturing, and transportation needs);
- *Affordability* (i.e., costs are within reach of latrine owners/users. Considerations include material, manufacturing, transport, and labor/installation costs); and
- *Acceptability* (i.e., preferences of owners/users are addressed. Considerations include installation and contextual requirements, longevity, and durability).

Effectiveness criteria stipulated that effective latrine pit design methods and materials must:

- *Prevent soil from entering the pit* (catastrophically or incrementally);
- *Enable moisture and gases to exit the pit* (ideally through the soil); and

- *Enable environmental microbes and air to enter the pit* (ideally through the soil).

Whenever possible and based on the information available, the desk review and interviews sought to identify the geography (sub-Saharan Africa, Asia), level of rural/remote, latrine type (wet, dry), installation requirements, transport requirements, and overall cost of any innovative materials and methods identified. Information on all criteria were not available for all examples, and the study team often relied on anecdotal evidence in the absence of published information. A list of all criteria for all innovations identified is provided in Appendix A. Country-specific experiences and anecdotal evidence from interviews are captured in Appendix B.

Twenty-nine KIIs were conducted as part of this study. Respondents brought experiences from many different countries and perspectives, including donors, nongovernmental organizations and implementing partners, other USAID activities, and material manufacturers and advisors. A summary of interviewees is provided in Annex C.

Following the initial compilation of results and sector-facing recommendations, WASHPaLS #2 convened a stakeholder consultation on February 27, 2024, to elicit expert perspectives and review, validate, and provide further detail to the Phase 1 findings. Fifteen experts participated in the consultation and several others provided written feedback via email. Experts engaged in the consultation are also identified in Annex C.

2.3 STUDY LIMITATIONS

A key limitation for this study was an overall dearth of documented evidence on lining practices, including little data on cost and scale of applications. Where it exists, cost data varies significantly from source to source, region to region, and over time, making price comparison difficult. Cost data on materials are also often not available for applications specific to sanitation or in the contexts under investigation, particularly in sub-Saharan Africa. Not all cost figures compiled were dated, and current cost data was difficult to find. Illustrative costs provided throughout this report are meant to provide examples to drive decision-making on the focus areas and innovations for future research.

Additionally, little data on latrine pit durability, defined as the ability of the lining to prevent collapse, and longevity, defined as the length of time the lining can remain durable, exists in published literature, as pit collapse is seldom researched and reported beyond the community level. The scale of collapse, and thus the potential of innovations best suited to individual contexts, is not well understood. Due to the limited availability of published research and evidence on pit lining, this report draws heavily on anecdotal evidence and responses from KIIs. Informants were often identified through individual recommendations surfacing during interviews, and this "snowball" approach to sourcing information may have resulted in other relevant examples and ideas being missed.

In general, pit lining needs and considerations vary not only country to country and region to region, but site to site. While the aim of this report is to provide a suite of robust options with potential to reduce costs while maintaining or improving structural integrity, site-specific considerations will be an important facet of any future research, piloting, and implementation. For testing and implementation, it is often difficult to convince masons and households to deviate from the materials and methods for lining that they know best.

3.0 FINDINGS

Throughout Phase 1, many experiences, lessons learned, potential innovations, and additional gaps and areas for future work/research were identified. These findings are summarized thematically by the conditions under which lining is needed (Section 3.1), considerations for constructing pit lining related to pit effectiveness and durability (Section 3.2), and examples of materials and methods that may provide cost-effective and durable alternatives or modifications to current options (Section 3.3).

3.1 UNDERSTANDING WHEN LINING IS NEEDED

Ideally, pit latrines are designed to hygienically contain and separate fecal waste from human contact and enable the treatment of their contents in situ, which generally requires interaction with the surrounding soil. An additional design consideration is whether to line the pit. Not all pits need to be fully lined, though all masons/builders should consider utilizing a collar/partial lining for at least the top half meter of the pit, as this provides structural support for the slab (Bob Reed 2014b). Lining decisions must be sensitive to context in design and application (captured as "varied lining requirements" in Figure 1); this diagram does not specify the various lining considerations and requirements for a given context. Additional information on these considerations is provided in Sections 3.2 and 3.3, and further detail on experiences, lessons learned, and potential solutions/options are provided in Annexes A and B. The general takeaway is that latrine pit lining is required in most circumstances, at least of the top half meter if not fully, unless these are dry pit latrines constructed in areas with highly stable soils (e.g., rocky or clay/loam soils) with low or no flooding propensity and that will not be emptied.

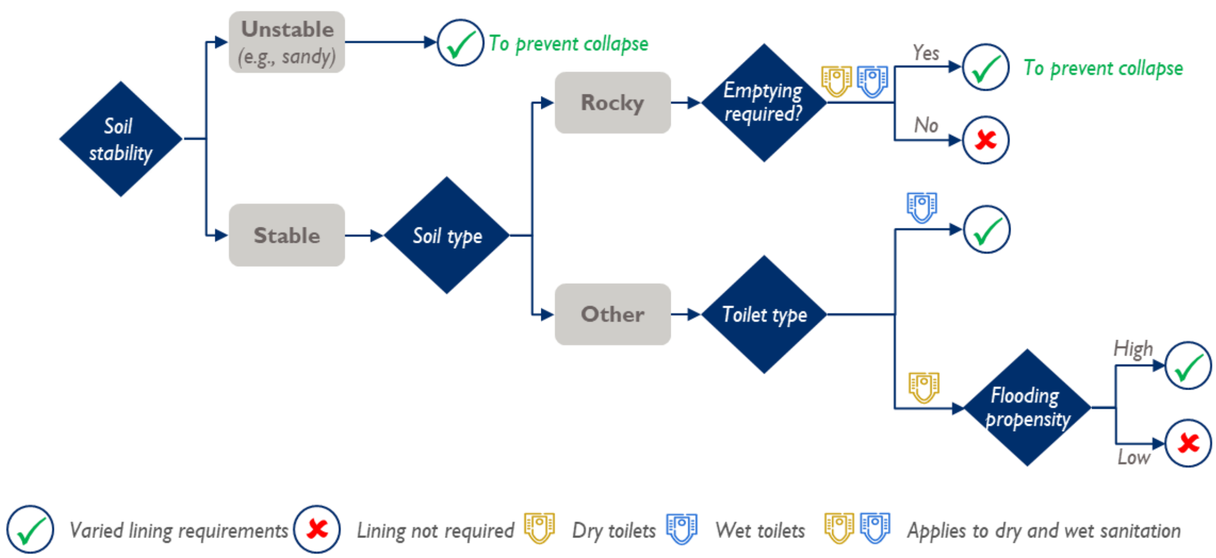

Figure 1: Conditions warranting pit lining

Lining often presents a sunk cost to consumers and barrier to affordability, particularly in areas where pits will not be emptied and reused. For this reason, among others, consumers often opt not to line their pits or to use low-cost locally available materials in contexts where lining is needed for structural stability, or not install a latrine until they can afford one with a lining. Choosing not to line a pit when lining is needed may result in collapse, whereas choosing to line a pit when lining is not needed (or choosing a lining option that is not best fit for that context) may represent an unnecessary expense. Poorly designed or unnecessary lining can result in increased fill rates and subsequent unsafe emptying or abandonment, with increased costs to consumers or a delay in installation.

Definitions of wet and dry pits in practice vary across contexts, and dry pits are sometimes operated in a wet state, such as when water for cleaning or cleansing enters the pit. For both dry and wet pits, there is a trend of increased moisture in pits across many contexts, either through increased water added to dry pits, such as through introduction of pour-flush latrine pans such as the SATO pan, or increased flows of wastewater and gray water into wet pits. For unlined pits, additional moisture in the pit increases risk of collapse. For sealed pits, additional moisture increases premature fill risk and associated emptying needs or abandonment.

Pit emptying necessarily introduces risk of exposure to pathogens at the surface, and where space constraints are not an issue and there is minimal risk of collapse or flooding, linings are not recommended. This is particularly relevant in many contexts in rural remote sub-Saharan Africa where pits are best taken offline once full, and another pit dug nearby. Poor construction practices are another significant cause of pit collapse, and not always solved by introducing a lining. The shape and depth of the pit, pit location, and materials/methods used for construction of the lining (if used), slab, and superstructure all influence the potential risk of collapse.

3.2 IMPACT OF LINING AND CONSTRUCTION PRACTICES ON LATRINE PIT EFFECTIVENESS AND DURABILITY

Overall, a lining is used to ensure the longevity and ultimate sustainability of a pit latrine, improving user safety, minimizing sunk costs by reducing the risk of collapse, and reducing the risk of abandonment and slippage to open defecation. To achieve these objectives, linings must be fit to context. For example, cement in southern Bangladesh is often degraded by brackish groundwater when not appropriately manufactured, reducing durability of the pit latrine lining. Similarly, treated/coated bamboo commonly used in arid regions of Nigeria and India may rot and decay if used in contexts with higher amounts of moisture (see Appendix B). However, despite their importance for structural integrity and safety, linings can reduce the effectiveness of latrine pits, particularly when sealed.

Fecal waste in latrine pits includes both sludge (solids) and effluent (liquid) that can be treated through natural processes in the presence of air (aerobic) or the absence of air/oxygen (anaerobic). Anaerobic processes are useful for reducing the volume of solids in the pit, which is important for slowing fill rates, but aerobic processes are important for the reduction of pathogens, including parasites, bacteria, and viruses. The oxygen-rich soil surrounding a latrine pit is extremely effective in pathogen neutralization. Effluent exiting the pit creates a naturally forming biofilm that slows effluent velocity and aids pathogen neutralization by the surrounding soil. Biofilms grow rapidly, performing effectively within the first 30 days of exposure to the effluent, and reaching optimum performance after one year. The biofilm area continues to expand over time, regulating the slow leach of effluent into the soil (Beal 2007).

Linings necessarily reduce contact between solids/liquids in the pit and the surrounding soil, which can limit pathogen reduction. In dry pits, aerobic processes are optimized by minimizing moisture content and maximizing airflow through the pit (Naughton et al. 2019). When liquid volumes are low enough, pathogens in the effluent exiting the pit are generally neutralized in the soil close to the pit walls. In wet pits, the pit acts like a septic tank, storing the sludge that accumulates over time. The area around the pit acts as a soak away, dissipating effluent (Bob Reed 2014a). In either wet or dry pits, unperforated linings with no way for effluent to leach out may result in premature filling of the pit and associated emptying needs, often due to the pit filling with liquid effluent.

When needed, linings should be perforated or permeable to reduce fill rates and keep the fecal waste in the pit as long as possible to maximize elimination and reduce exposure to harmful pathogens. Linings are sometimes implemented in ways that fully seal pits, particularly for wet pits and in areas with high groundwater tables or flood-prone regions. This practice is partly driven by perceived groundwater contamination risks writ large, rather than actual risks to groundwater sources from nearby latrine pits.

This presents a trade-off: fully sealed pit linings increase pit fill rates and the need for premature emptying, while latrine pit effluent from perforated pits may pose contamination risk, though the level of this risk is poorly understood. Additional research is needed to better understand pathogen travel and transport in a given site (Graham and Polizzotto 2013), though guidance is often widely available on placement of pits near water sources. Sealed pits with quicker fill rates not only increase costs to households, but also increase risk of pathogen exposure if pits need to be emptied before natural treatment processes have run their course, or if they have been inhibited by the design of the lining. Many rural areas still have no safe pit emptying and disposal options at all.

Across contexts and for both wet and dry pits, durability and effectiveness are impacted by poor construction practices and low-quality materials. Even where concrete and brick linings are more affordable and widely implemented, collapse and/or high fill rates can be caused by poor design and construction, often due to nonexistent or limited implementation of standards and guidelines, low skill levels and limited training opportunities, and limited oversight and quality control. Where they exist, national-level guidelines and preferences for latrine pit design vary substantially from country to country and set the standard for materials and methods used in latrine pit design and construction. Additionally, international-level guidelines on safe distances between pits and potable groundwater sources currently imply that it is never safe to construct pits in saturated soil, resulting in many fully sealed pits even where not required. The WASH sector generally faces a lack of consistent guidance on latrine pit design and construction, particularly impacting consumers and masons/builders who need this guidance most.

3.3 BEST-FIT MATERIALS AND METHODS FOR PIT LINING ACROSS CONTEXTS

From KIIs, desk research, and the wider stakeholder consultation process, we identified many alternative materials and methods with potential to address the cost, durability, and marketing challenges that the marketing of current lining options face. Materials were assessed based on effectiveness for pit lining and on the marketability criteria outlined in Section 2: availability, applicability, affordability, and acceptability. They are discussed below and presented in more detail in Appendix A. Appendix B includes a description of pit lining practices and materials by region and country.

Broadly speaking, manufactured materials, including bricks, concrete rings, plastics, metals, and geotextiles (e.g., fabrics and earth-based woven materials), may be robust enough to address durability challenges across contexts, but affordability and consumer acceptability constraints must be addressed, particularly in sub-Saharan Africa. Alternatives and materials to supplement/reduce the need for concrete and bricks hold potential for reducing the cost of lining in sub-Saharan Africa, but they also face more significant supply chain challenges and limited research/proof of concept in this region. Natural and recycled materials are context-specific and, while often affordable and preferred by households where available, have little market potential where they are not abundantly available or cannot be centrally manufactured or produced.

3.3.1 TESTED ADJUSTMENTS AND ADDITIVES TO BRICK AND CONCRETE PIT LININGS

Bricks and cement are the most common materials used for latrine pit lining in low-income contexts. These materials are commonly produced and available due to their multi-purpose use cases (building construction, water mains and wells). Bricks and/or concrete blocks can be stacked as they would be for other construction purposes, sometimes with spacers between the blocks to allow seepage. Pre-cast concrete rings are also often used for pit lining, often stacked for deeper pits, and are particularly common across the Asia region. These rings face transport issues due to their bulky size and shape, and can break en route to the site, particularly when low-quality cement is used. Regardless of their size and shape, bricks and concrete are heavy, increasing transport costs. Several adjustments to and additives for concrete and brick manufacturing have been trialed and tested to reduce costs and improve pit performance and reduce fill rates while ensuring pit durability and preventing collapse.

Alterations to the standard concrete ring lining have been implemented around the world with varying levels of success, particularly in the Asia region. iDE has developed a concrete mix to construct rings for pit linings that are lighter, thinner, and overall, less expensive than rings made from typical concrete construction mixes. The rings are typically installed in a single pit, 3-ring stacked design (Harper 2019). The full latrine cost is less than 20 percent of a standard concrete latrine in Cambodia, with an average retail price of USD 65, partially due to thinner pit lining rings, less expensive materials used in the concrete mix, a more affordable superstructure, and a facilitated supply system with embedded sales agents (iDE 2019, iDE 2009).

Two concrete mixtures and associated designs are currently implemented: dry concrete rings (Figure 2) and wet concrete rings (Figure 3), both used for wet pit latrine applications. The dry concrete rings have a diameter of 0.8 m and a relatively high quantity of gravel and large aggregate to increase porosity and exfiltration. The wet rings have a diameter of 1.0 m and are a more standard concrete mixture, but due to their low porosity and correspondingly higher fill rates, they are made larger to hold a higher volume. The dry rings break more easily than the wet rings, resulting in transport challenges and associated higher costs. Wet rings have a higher production cost and are also often used in flood-prone areas in Cambodia, featuring stilts with pipes that run into the ground (Sky Latrine design, see Figure 3). However, latrines with both dry and wet rings are subject to quicker fill rates due to poor seepage in clay-heavy and other densely packed soils in Cambodia. iDE has installed over 400,000 Easy Latrines in Cambodia using these dry and wet ring designs. This product has shown high marketability in the Cambodia context, likely thanks to its correspondence to household aspirations for higher end products, the price-point in range of consumer willingness-to-pay, a road network facilitating transport of the rings, and relatively high rural density aiding sanitation business viability. The wet and dry concrete rings were designed for the Cambodian market and have not been marketed elsewhere, though concrete rings in general have been employed for pit lining across most of Asia and much of sub-Saharan Africa. Their potential to address affordability, availability, and acceptability constraints is unlikely in most African contexts due to poor road conditions and networks, lower willingness to pay, and more dispersed rural populations. Further exploration of these concrete ring mixtures and modifications should focus on contexts where they have the strongest potential for successful marketing, sales, and adoption, including other Asian contexts.

Figure 2: Dry Ring for iDE's Easy Latrines in Cambodia (source: iDE Cambodia)

Figure 3: Wet Ring for iDE's Easy Latrines in Cambodia (left, source: iDE Cambodia), used for Sky Latrines constructed on stilts for seasonally flooded areas (right, source: Water For Women Fund)

Clay rings are another alternative to concrete rings and are commonly used to line groundwater wells. Clay rings have lower material and labor costs than concrete rings, but their availability is limited to regions with a natural abundance of clay, suppliers with the required skills and equipment, and transportation if pre-cast. As with more typical concrete rings, clay or ferrocement rings can be constructed to allow liquids to leach into the surrounding soils by either drilling holes in the finished product or, preferably, incorporating perforations in the manufacturing process by setting small rods/pipes into the material while wet and removing them once it has dried. Clay rings are much more susceptible than concrete to breakage during transport, limiting their market potential unless they can be feasibly cast on-site. Due to transport challenges and material limitations, clay rings are not likely to be highly marketable and scalable.

Ferrocement and chicken wire are commonly used in residential construction as an alternative to concrete, reducing cost due to the smaller volume of materials needed (Grossnickle et al. 2017). This lining option likely costs USD 30-50 for a latrine with a depth of 1.5 meters and a diameter of 1 meter, depending on the local cost of cement and assuming up to 2" of cement thickness (Grossnickle et al. 2016). A few layers of steel mesh such as chicken wire are set into a mortar-lined pit, and sticks or other spacers added to ensure perforation. A second layer of mortar is then added to ensure the wire mesh is completely covered. Ferrocement and wire mesh would likely reduce material costs due to the lower quantity of cement needed, though little evidence on cost comparison is published. For example, ferrocement has been demonstrated to allow thinner slabs than traditional reinforced concrete (Brian Reed 2012). While installation requires some skill to ensure no reinforcement is exposed, cement and chicken wire are generally widely available in many rural markets and transport to site would be easy as the components are lightweight and not breakable. Lower costs compared to traditional concrete, widespread availability of materials, potential for self-installation with minimal training/guidance, and limited transport challenges render this innovation worth testing as likely marketable for pit lining.

Rebar-reinforced fabric lining (Figure 4) is another viable alternative, costing up to approximately USD 40 per lining for a latrine with a depth of 1.5 meters and a diameter of 1 meter (Grossnickle et al. 2017). Most of the cost is from the rebar, though scrap materials may be able to reduce the cost if available locally. Rebar-reinforced fabric linings have been demonstrated to withstand soil pressure and hold shape when used for pit lining. The rebar, wire mesh, and fabric needed are available in most contexts and will allow liquids to leach into the surrounding environment if the fabric is permeable. Depending on the cloth material used, this lining design may resist degradation over time, though it is best suited to dry pit applications to avoid potential rusting of the rebar and mesh and degradation of the cloth. There is no evidence on the longevity of this design, and there is no evidence to date of its widespread implementation. Determining at-scale application and marketability of this material for pit lining would require further testing, particularly to understand ideal fabrics/materials and longevity.

Figure 4: Rebar-reinforced fabric lining (source: CAWST)

CAWST has piloted cement reinforced stabilized soil lining in Liberia (Figure 5), initially developed by iDE. A small amount of cement is added to soil excavated from the pit with minimal water, and placed in between the pit walls and a mold that is placed in the center, leaving a gap for the lining to fill. While the mold itself may be difficult to acquire, materials are otherwise widely available, and labor/installation costs are low. Given that this method utilizes locally-available resources in most markets and does not require heavily-skilled labor, it may present a cost-effective and marketable option.

Figure 5: Construction of cement-reinforced stabilized soil lining (source: CAWST)

In summary, a few adjustments and additives to concrete pit linings warrant further testing of widespread marketability and effectiveness for pit lining. The iDE Easy Latrine linings may address marketability challenges with standard concrete rings in contexts like Cambodia. Ferrocement and chicken wire linings, cement reinforced stabilized soil linings, and rebar-reinforced fabric linings may reduce lining costs by up to 30-50%, are likely attractive to the market due to limited installation needs, and show the most potential for further testing to ascertain their cross-context applicability and marketability. Additionally, rebar-reinforced fabric linings and cement reinforced stabilized soil need further research on their effectiveness as a pit lining material (e.g., durability).

3.3.2 SPECULATIVE ALTERNATIVES TO BRICK AND CONCRETE WITH POTENTIAL FOR LINING

There are many alternatives to concrete and bricks used in construction around the world due to the recent increasing costs of cement and aggregate, a desire to create more eco-friendly building materials, and the need for quicker and easier installation. These materials are commonly used in residential, road, and drainage construction. While there is no proof of concept to date of these innovations being used for pit lining, further research and testing may demonstrate their potential for sanitation applications.

Natural fibers such as hemp are increasingly used in concrete alternatives. Hemp is the longest and strongest natural fiber in the world, with promising construction applications in low- and middle-income countries (UNCTAD 2022, Ahmed et al. 2022). Hempcrete is created by binding the core fibers of hemp with lime as a binding agent and is one-eighth the weight of concrete (Roberts 2020). The legality of growing and processing hemp varies around the world, however, with many countries facing legal battles to its widespread use, particularly in sub-Saharan Africa. South Africa currently has the continent's only hempcrete manufacturing facilities. Prices for a 30 cubic centimeter block of hempcrete (Figure 6) can range from approximately USD 20–30, depending on the country and market. For comparison, a standard concrete block in Uganda (as in many other countries in sub-Saharan Africa) costs less than USD 1 (Daily Monitor 2020). Beyond manufacturing, cost, and legal challenges, the material's capacity to retain water, resulting in swelling and eventual decay if not sealed or treated, renders hempcrete less suitable for the moist conditions of even dry pits. Additionally, there is a lack of evidence of its compressive strength and ability to be used for load-bearing construction; there also is limited evidence of its use for subterranean and soil-retaining purposes. Hempcrete therefore does not present a strong case for further testing for pit lining application and marketability.

Figure 6: Hempcrete blocks for residential construction (Source: HempBuild Magazine)

Concrete cloth, or concrete canvas (Figure 7), is another alternative to standard pre-cast concrete lining rings. Common construction applications include road pavement, culverts and channels, and emergency response settings. It is widely regarded for its ease and speed of installation and is available in many countries across North America, Europe, Asia, and Africa. The material is commonly sold as a roll or large sheet, which is molded into the required shape, covered in cement in overlapping areas, nailed or otherwise fastened, and then saturated with water, hardening as it dries. Concrete cloth sets within 24 hours at up to 80 percent strength, continuing to gain strength over time. The product is lightweight and compact and may thus reduce transport costs compared to pre-cast concrete rings. Costs range from USD 20–50 per square meter, for a pit latrine with a depth of 3 m and a diameter of 1m this lining would cost around USD 200-500.[3] It often comes with a PVC backing on one side for impermeability, which may limit pit effectiveness if not removed. This solution holds potential for both wet and dry pit

[3] A latrine pit that is 3 meters deep and 1 meter in diameter would require approximately 9.5 m^2 of material.

applications and may be suitable for flood-prone areas as well, but overall cost of the material, the need to potentially adapt it to ensure permeability, and unknowns around the potential to introduce it to rural markets, render concrete cloth an unlikely solution for at-scale marketing for pit lining.

Figure 7: Rolling out concrete canvas during construction (Source: Geosynthetics Magazine)

Gypsum, commonly used to create drywall, is a very lightweight alternative to concrete at a comparable price. It is available in many cities and market centers around the world, although manufacturing is currently limited to primarily high-income countries. While gypsum has historically not been used for load-bearing construction purposes, innovations such as high-density gypsum have been used to construct entire homes and may exceed the strength of standard concrete mixtures in many applications. Gypsum can be cast and molded into a wide variety of shapes, but its lack of moisture resistance may limit its potential for pit lining; while some innovations show potential for moisture-resistance, fully waterproof gypsum options are currently unavailable. Gypsum may be marketable thanks to its reduced transport costs and broader construction applications, but its application to pit lining is limited by current lack of moisture resistance and active supply chains. Further testing of effectiveness and marketability will be dependent on the development of better moisture-resistant options.

In addition to direct alternatives to concrete, there are many natural resins, additives, and biopolymers that can be added to concrete mixtures or directly to the soil; these may hold promise for reducing material costs for lining. Additives such as unground rice husk (Hwang and Huynh 2015) and plantain fiber (Edike, Sotunbo, and Yohanna 2019) provide potential to create strong, eco-friendly, and potentially cheaper bricks and concrete from agriculture waste. These are unlikely to be a marketable product for lining in the immediate future due to a lack of central manufacturing potential at an affordable rate. If demand for these products continues to rise, e.g., due to increased demand for eco-friendly construction materials, the possibility of central manufacturing and reduced prices may increase.

Biopolymers such as xanthan gum can be used to stabilize soil, increase its compressive and shear strength, and reduce the need for lining altogether (Sulaiman et al. 2022, Latifi et al. 2016). Xanthan gum is particularly useful in clay soils due to the strong electrostatic bonds that it forms with clay particles. Xanthan gum costs just over USD 10 per kilogram and is readily available at food additive stores in most urban areas and market centers. Additionally, natural resins/coatings such as EarthEnable, K31-APS, and AggreBind can help to stabilize clay and sandy soils to improve their compressive strength, and can also be added to soil to create a material alternative to concrete or cement blocks. The cost is moderate at only USD 5–10 per liter, though resins are currently only manufactured in North America and Europe. To produce blocks, up to 4 liters of resin are needed per cubic meter of blocks produced. Blocks produced with these resins have a compressive strength comparable to or higher than many concrete mixtures, and these have been used primarily for residential flooring and road pavement to date. Application of resins/coatings by local masons or builders will likely be straightforward, similar to the use of other binders or sealants, including cement and silicone/latex. While there are availability and manufacturing limitations, the use of resins or coatings to stabilize soil or combine with other (natural) pit lining materials holds promise for increasing durability at a relatively low price point. Opportunities should be explored to further test the use of resins/coatings in (permeable) pit lining applications, and also to increase understanding of the potential for local manufacturing, development of supply chains, and affordable marketing across rural markets.

In summary, of the alternatives to bricks and concrete explored for which no pit lining proof of concept exists, the use of biopolymers and natural resins holds highest potential for further exploration.

3.3.3 PLASTIC LINING AS A DURABLE, LIGHTWEIGHT, AND COST-EFFECTIVE ALTERNATIVE

Manufactured plastic pit linings also provide a promising alternative to concrete. However, the commercialization of perforated plastic liners in rural contexts requires developing business models and end-to-end supply chains. While lightweight and durable plastic construction materials such as plastic bricks are beginning to be manufactured in sub-Saharan Africa and hold promise for lining applications (UNICEF 2019), there are also several ready-made plastic linings on the market or in development now.

The SATO Pit Liner by LIXIL (Figure 8) is currently in the prototype stage with ongoing field testing in India, Uganda, Malawi, and Zambia. The current design has proven to withstand substantial soil pressures and features plastic panels that fasten together to form rings, which can be stacked and fastened before being placed in the pit. The lower portion of the plastic lining is perforated to allow leaching into the surrounding soil, though a design for flood-prone contexts is underway and will likely be fully sealed. A set of 18 panels is likely to cost USD 65–75.[4] While the lining will currently need to be imported and transported to the site in most contexts, it is very lightweight and compact in size, making it a suitable alternative to standard lining materials in hard-to-reach areas. The SATO Pit Liner is designed to be implemented with the SATO pan and is thus well suited to wet pit applications, and it would also function well for dry pits. As the product is still in the prototype stage, further testing is recommended to confirm broad marketability, including consumer response and satisfaction, willingness to pay, and ease of incorporation/integration into existing supply chains and product offerings by local sanitation businesses or hardware store owners.

Figure 8: SATO Liner prototype at the AfricaSan 7 conference (source: Carolien van der Voorden)

[4] 18 panels are sufficient for a latrine that is 1.5m deep and 1m in diameter.

The Digni-Loo (Figure 9), designed by Global Communities under the USAID WASH for Health program, provides another durable and lightweight plastic pit lining option (Borkowski and Perez, n.d.). The Digni-Loo includes a slab and adjustable unperforated liner for USD 81. The Digni-Loo is currently only implemented at-scale in Ghana, with over 30,000 sold. The lining and slab are easy to install and lightweight to transport. The Digni-Loo lining should be perforated to allow increased seepage and reduce fill times, as quick fill rates and associated emptying needs increase costs to households, and may limit customer satisfaction and associated marketability.

Plastic linings such as the Digni-Loo and SATO Pit Liner enable safe emptying in contexts where emptying is a viable option, and, in theory, may be able to be removed and reused in a new pit as part of a full suite of SMSS. Reusable linings would reduce sunk costs to households, but public health and safety considerations should be the priority for any research and testing of this possibility of removal and reuse. There is limited evidence of this being successfully done.

In summary, plastic liners hold promise for wide application and marketability thanks to their lightweight, strong, durable, and affordable nature, provided they can be manufactured regionally or locally or imported at relatively low cost, and easy to transport. They are recommended for further testing on acceptability, viability, and safely managed sanitation potential.

Figure 9: Digni-Loo installation in Ghana, showing the full lining (left) and the final installed product (right) (source: Global Communities Ghana)

3.3.4 NATURAL MATERIALS AND THEIR APPLICATIONS IN PIT LINING CONSTRUCTION

Natural materials are often used for lining, including bamboo, rocks, coconut shells, and coral, and have little to no cost when households can locally source these materials themselves, except for the labor or effort to acquire them. There are examples of successful use of bamboo in several African and south Asian countries (WaterAid, n.d.), including bamboo interwoven with small branches in northern Nigeria and northeast India. Baked bricks made of local clay, such as those used in Zimbabwe and West Africa, and stabilized soil blocks also fall within this category, often manufactured at the household level with little to no cost. Baked bricks and other soil blocks are often handmade or require special machinery, and are very labor-intensive, limiting their market potential. Natural materials like bamboo are often covered in thin layers of concrete for reinforcement, though natural resins may also be used.

Stacked rocks (see cover photo) have been successfully employed in areas with collapsible soils and a wide abundance of flat sheet rock, such as parts of Uganda, Zimbabwe, and Bhutan. Small amounts of cement or fine rocks and aggregate are often used as filler material. Care must be taken when stacking these rocks to ensure their stability, often done by local artisans with sufficient experience constructing stacked rock lining and other structures. Gabion walls, cellular structures used across North America and Europe for retaining walls and landscaping, employ zinc-coated steel wire mesh to hold similarly stacked rocks together. While there are no examples of gabion walls being used for pit lining applications, the use of a metal wire mesh may ease the construction of stacked rock pit linings without a substantial increase in cost, increasing their viability in areas where artisans and stone construction knowledge are limited, and reducing labor costs. Given the lightweight nature of steel wire mesh/frames, transport costs would be minimal in areas where flat, stackable rocks are abundant. Gabion or wire mesh has high market potential. It is widely available across parts of Southeast Asia and India, and some countries in Africa, and could likely be widely introduced into supply chains. It is affordable (prices range from USD 1 to 30 per m² for standard gabion), durable, and can be used with a variety of locally available rocks, stones, or other materials.

In general, natural materials are acceptable and often preferred by consumers due to the low material cost and ability of consumers to provide in-kind contributions to construction. Their applications for lining require specialized knowledge from local artisans to ensure structural integrity, durability, and proper functioning. Natural degradation of many of these materials can limit their structural integrity over time, but the addition of common construction materials available in most contexts such as metal wire, small amounts of concrete, or biopolymers or resins, can significantly increase their durability and longevity while providing a cost-effective alternative to concrete- and brick-lined pits.

In summary, while highly local, natural materials may have low marketability due to localized availability, limited supply chains, specialist skills requirements, or potential high costs for transport (e.g., for stackable rocks), they can become part of a scalable solution when combined with a marketable material that can provide structure to, or ease use of, the natural material. In this respect, the application and marketability of gabion or other wire mesh for pit lining warrants further exploration.

3.3.5 RECYCLED/REPURPOSED MATERIALS AND THEIR APPLICATIONS IN PIT LINING CONSTRUCTION

Recycled materials, including old tires and oil drums, are sometimes used for pit lining with little to no cost when available locally; they are commonly used in the Solomon Islands and other Pacific Island nations. While recycled materials are often available in urban areas and market centers, transport to more rural areas impacts affordability. Shipping containers have even been used for larger-scale latrine applications in emergency contexts (Brian Reed, Torr, and Scott 2016). Many recycled materials may pose design constraints due to size (such as the small inner diameters of tires) and gradual corrosion, reducing their lifespan and increasing risk of collapse. Ease of self-installation for recycled materials also weakens the business case for professional service development. These materials are likely best suited to cases where structural support is needed temporarily or customers are prepared to construct new toilets every 2–3 years.

There are many potential innovative applications for recycled materials. Ground plastics, such as from bottles, can serve as a filler for concrete blocks to reduce the overall material cost, particularly in sub-Saharan Africa where cement costs are high. Examples were found of their use for construction of houses and schools in refugee camps in Bangladesh (Haque and Islam 2021). Eliminating cement altogether, eco-bricks are plastic bottles manually filled with additional sources of waste plastic and other inorganic waste (Antico et al. 2017). Eco-bricks are used for load-bearing construction in houses and other small structures, and they have been used to construct water storage tanks with a capacity of up to 23,000 liters. Eco-bricks have been used in construction in Uganda, Bolivia, Senegal, Mexico, and Colombia, but there are no published examples of subterranean applications. As with other recycled materials, this innovation requires a reliable stream of waste and quality control to ensure consistency in source materials. While there are little to no material costs for the use of recycled plastic where it is available, assembly can be time- and cost-intensive. Additionally, there is a risk of chemicals from recycled plastics contaminating the surrounding environment over time. Marketability of eco-bricks for pit lining is considered low, due to the time-intensive labor needs and limited potential to widely scale.

Sandbags are a commonly repurposed commodity in refugee camps and have been studied as a cost-effective alternative lining option. Sandbag linings can cost up to USD 30 per latrine[5] (Grossnickle et al. 2017). While installation can be labor-intensive due to the weight of the sandbags, no specially trained masons or builders are required, reducing installation costs, and increasing ease and speed of implementation. Empty sandbags are also lightweight and easy to transport, and they can be filled with the soil excavated for the pit at no extra cost. While there is little evidence available on longevity, this is strongly dependent on the bag material, and pits are likely to fill before the sandbags themselves degrade. If they are designed and implemented with sufficient spacing, liquids can leach into the surrounding environment with sandbag linings. However, depending on the material, plastics from the sandbags will remain in the soil and may also leach chemicals into the surrounding environment over time. Thanks to their widespread availability, affordability, ease of transport, and ease of use, the potential application and marketability of sandbags for pit lining is promising, but attractiveness and acceptability of this solution warrants further exploration.

Mesh linings from old fishnets have been used in Bangladesh and may hold potential in coastal communities, but they would likely need to be implemented with additional reinforcement, such as rebar, or with a soil-stabilizing agent.

In summary, sandbags hold the most promise for pit lining among recycled and repurposed materials. Like the wire mesh and resin solutions discussed above, they provide an affordable structure for the use of excavated soil and/or rocks on premises. There may be broader applications of these materials beyond pit lining, which adds to their likely marketability by rural hardware stores and entrepreneurs.

3.4 REFLECTIONS, GAPS, AND BARRIERS

Several key reflections, gaps, and barriers emerged from the desk review, KIIs, and stakeholder consultation process. Overall, there are some pit lining solutions that work well in some contexts, and several innovative materials and methods that hold promise, but the following reflections and gaps are notable:

1. Latrines that require linings to improve structure integrity often go unlined, largely due to affordability constraints. A general lack of knowledge regarding when lining is needed (and what solutions are best fit to the local conditions) is widespread.
2. Common materials used in lining such as bricks and concrete rings are prohibitively expensive in rural sub-Saharan Africa, but some alternatives and options have been identified with potential to address affordability concerns. To date, however, there is limited demonstration of widespread market potential and proof of concept for their use in pit lining. There are many areas for further research on innovative concrete and brick alternatives, on additives and stabilizers that can improve soil strength and minimize lining needs, on the use of natural and recycled materials to reduce material costs, and on the marketing and sale of plastic latrine pit linings. Specific recommendations for further research are provided in Appendix A.
3. Construction materials and methods are largely driven by what local masons and builders know and trust best, and current incentives result in masons promoting heavy and more labor-intensive materials such as concrete. Lined pits are thus often constructed fully sealed, leading to increased fill rates and associated emptying needs, resulting in increased cost to consumers.
4. Lining materials and methods must be context-specific, and the level of scale in supply chains for innovative materials may depend on other use cases within a given context. For example, natural

[5] A latrine pit that is 3 m deep would require approximately 80 sandbags at an average cost of USD 0.375 per bag .

polymers and resins have applications in flooring for buildings and even road pavement, which may increase their availability and reduce their market price over time with multiple sectors relying on them for construction. That said, even within a given country or region, soil properties, groundwater levels, consumer preferences, local practices, and other considerations must be balanced in decision-making for pit lining and will impact the market viability of potential innovations.

5. There are limited solutions for lining pits effectively and efficiently in flood-prone areas or inundated soils, particularly in sub-Saharan Africa. It is important to balance risks between groundwater contamination and contamination at the surface, considering the larger system (or lack) of SMSS. Emptying is not a viable option in many rural remote areas and should not be encouraged where unsafe, supporting the need for effective, perforated linings.
6. There is limited understanding of key concepts, techniques, and options for latrine pit lining (materials, construction techniques, best practice to ensure effective operations) among those setting and enforcing standards and practitioners, resulting in either a lack of regulation or overly restrictive regulation of construction practices and services and inconsistent implementation of guidelines and best practices. Technical guidance on lining options and best construction practices could go a long way to supporting authorities in this process, but the political will and monitoring mechanisms must be in place for this to happen.

4.0 RECOMMENDATIONS FOR PIT LINING INNOVATION

WASHPaLS #2 proposes several recommendations for pit lining innovation as well as a list of other potential areas of exploration that surfaced during Phase I.

4.1 RECOMMENDATIONS

1. **Pilot application and marketability of perforated, permeable, and lightweight concrete latrine ring liners:** Concrete linings will likely continue to be common in many contexts, so improving their affordability and transportability is an important area of study. Additional research should continue finding ways to manufacture lighter weight concrete using the many additives and approaches outlined in Section 3.3. Consumer acceptance, cost, and marketability of modified building materials will be important factors to ensure efficiency in implementation. Additionally, improving their effectiveness is worthwhile to reduce fill rates and ensure effective pit operations. Construction methods and market acceptance of concrete liners that are permeable, manufactured with additives or biodegradable aggregate such as the iDE dry concrete rings, should be explored further in the contexts where they have the most likely marketability. Additionally, perforated concrete lining, manufactured with holes, is an alternative option warranting additional research.
2. **Test marketability of perforated plastic pit liners:** Plastic pit liners have strong potential to address cost, transportation, and effectiveness concerns. Additional research is needed to understand all marketability criteria, including consumer acceptance, affordability, and supply chain development of linings such as the Digni-Loo, SATO Liner, and other competitors. Additional research also could investigate the ideal length/width/shape of perforations, given the ease of quality control during manufacturing. Designs of plastic linings for flood-prone areas should be conscious of pit effectiveness criteria and availability of emptying services nearby.
3. **Identify and test new materials for latrine pit lining:** New materials for pit lining should continue to be explored and identified to prevent collapse and overcome efficiency challenges posed by current materials, designs, and construction practices. They should also be tested for marketability, particularly those materials that have already shown proof of concept for pit lining applications. Full details on materials examined and recommendations for further research are provided in Appendix A. The most promising materials for further exploration include:

    a. Rebar-reinforced fabric and ferrocement and chicken wire may ease and increase consistency of construction and reduce costs associated with transport and labor. These materials are likely widely available in rural markets and have use cases in other sectors and construction needs that could increase their market potential and further reduce cost. Further testing of both marketability and effectiveness is needed
    b. Natural resins, biopolymers, and cement reinforced stabilized soil should be examined for their potential to increase soil stability and reduce the need for lining, which may pair well with cheaper but less durable lining materials, including natural materials such as bamboo
    c. Alternatives to bricks should also be explored further, including plastic eco-bricks and other stacked-block alternatives
    d. Marketable materials that can provide structure to, or ease use of, natural materials found locally, such as gabion or wire mesh to ease the construction and potentially improve the durability of stacked stone, or sandbags that can be filled with excavated pit materials

    Combinations of potential materials identified should be further explored for their potential, such as bamboo coated with natural resins to increase durability, or soil stabilizers to reduce lining needs with thinner concrete rings. Given limited proof of concept for many of these potential innovations, in addition to investigating marketability, field testing should examine strength under soil pressure, interactions with moisture in pits and in the ground, and any impacts to the surrounding environment due to leaching chemicals.

4.2 OTHER AREAS OF EXPLORATION

4. **Develop latrine pit designs for challenging contexts:** In many contexts, including flood-prone areas, areas with high groundwater tables, humanitarian settings, and areas with dense silty or clay soils, further research on ideal latrine pit designs and lining options is needed. Several innovative materials and methods hold promise for these applications but currently have no proof of concept for latrine pit lining. For example, materials that are lightweight and can be erected quickly such as concrete cloth may be suitable for refugee and internally displaced persons (IDP) camps, and natural resins may help to waterproof natural or recycled materials in areas with seasonal flooding.
5. **Understand the knowledge, attitudes, and practices that lead to non-perforated pit linings and poor construction practices:** Additional research is needed on the contexts (e.g., high water table, cheap concrete liners), guidance (e.g., sanitation guidelines, National Building Codes), and/or historical practices (e.g., dry pit toilets) that result in sealed pits. Additionally, future work should raise awareness on the role of biofilms in treating effluent leaving the pit among those involved in standard-setting and practitioners in the private sector. The incentives leading to poor quality construction and sub-standard materials in the market should be further unpacked and addressed, which will require context-sensitive interventions.
6. **Improve the evidence base on the relative magnitude and breadth of pit lining collapse:** Many challenges related to pit collapse are context-specific, and little data is available to show the varying conditions across contexts that lead to pits collapsing. With more evidence of these challenges, practitioners can implement designs that are better fit for context to improve durability while also addressing marketability and effectiveness criteria. Additionally, knowledge of the relative population sizes impacted by each unique challenge would provide evidence for practitioners to prioritize solutions to develop in the market and scale.
7. **Integrate and disseminate guidance to help authorities understand and regulate best practices for construction of latrine pit lining:** Latrine pit collapse is likely often attributable to poor construction practices, and masons/builders are often reluctant to implement methods and materials with which they are unfamiliar. This can result in a lack of perforations in sidewall construction; construction of pits that are poorly sized or shaped, contributing to collapse; or construction with no lining at all, or without a collar at the top of the pit where this would suffice. Guidance needs to more effectively reach practitioners, including masons and informal builders, on the conditions under which pits should be lined and best-fit options for lining in each context. Technical guidance and a compilation of options and best practices, if integrated into relevant sanitation and/or construction guidance, would enable authorities to provide oversight and regulation, potentially reducing pit collapse. Increased awareness of the principles underpinning latrine design and evidence of local conditions and safe setback distances from water sources is also needed to inform context-specific guidelines. Relative risks posed by contamination to groundwater and contamination to the surface must be carefully considered. Guidelines and construction standards then need to be applied in practice by masons/builders, which can be encouraged by development partners in-country.

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APPENDIX A: SUMMARY TABLE OF MATERIALS AND METHODS REVIEWED

Material	Proof of concept for pit lining?	Typical applications/use cases	Material type/additional details	Availability *Material sourcing, manufacturing, and transportation needs*	Affordability *Material, manufacturing, transport, and labor/ installation costs*	Applicability *Installation and contextual requirements, longevity, and durability*	Recommended for further research and testing?
Eco-bricks (plastic bottles manually filled with plastic, sand, or other materials)	No	Used in conjunction with adobe and natural earth building materials for load-bearing construction. No below-ground proof of concept. A bottle of any size is filled with small pieces of pliable household plastic, though sand or dirt could also likely be used. Once compact, the bottle is then used as a brick equivalent with large amounts of clay/adobe or other binders to create a structure. Used to build houses, schools, and water tanks in various countries (Uganda, Bolivia, Senegal, Mexico, various cities in Latin America, Colombia, Indonesia and Nicaragua).	Plastic bottles filled manually with additional plastic waste, sand, dirt, or other readily available fill material, to create a solid brick-like product. Material to be used for lining; a substitute for more common brick/block-type building materials.	Not mass manufactured or generally available in existing markets. Time and labor intensive as they are handmade and dependent on availability of local plastic waste and readily available sand/fill in the area.	Minimal material costs as they are made from recycled plastic. They may require mortar to bind the bricks together. Transportation costs are minimal when manufactured on-site and the labor/installation costs are comparable to standard bricks as they function the same in construction.	No evidence of longevity given no proof of concept for similar applications. Contents of the bottle are inconsistent in strength as the mechanical properties of each product are dependent on the filler. The strength of the eco-brick when filled with plastic can be up to 2.55-2.9 MPa and when filled with sand 27-38 MPa. For reference, the average compressive strength of a concrete hollow block is 3.5 MPa and 17 MPa for a concrete solid block. Risk of chemicals leaking in to the surrounding environment needs to be further evaluated.	No - limited market potential due to time-intensive labor needs and limited potential to widely scale.
Eco-bricks (concrete bricks with plastic bottles as a filler)	No	Load bearing for buildings. No below ground proof of concept. Used above grade for low-cost housing in Bangladesh refugee camps.	Similar to a cinder block as it is a concrete brick with a plastic bottle in the middle that provides a void. Material to be used for lining; a substitute for more common brick/block-type building materials. Can be bound with mortar or clay.	Not mass manufactured or generally available in existing markets. Time and labor intensive as they are handmade and dependent on availability of local plastic waste.	The material and manufacturing costs are slightly cheaper than for standard bricks due to the use of bottles/void to reduce material needs. As these are produced locally or on-site, transport costs are minimal. Labor/installation costs are comparable to standard bricks as they function the same in construction.	No evidence of longevity given no proof of concept for similar applications. Average compressive strength value of 4.30 MPa, beyond the standard value for concrete hollow blocks (3.5 MPa). Risk of chemicals leaking into the surrounding environment needs to be further evaluated.	No - limited market potential due to time-intensive labor needs and limited potential to widely scale.
Eco-bricks (plastic bricks made of mostly recycled plastic, manufactured)	No	Load-bearing for buildings. No below-ground proof of concept. Used above grade to construct houses and schools in Colombia and Côte d'Ivoire. Recycled plastic walkway pavers used in Kenya.	Brick product made from recycled plastic. Material to be used for a lining; a substitute for more common brick/block-type materials.	Not widely manufactured, particularly in low-income countries. Mostly manufactured in the United States (US), Europe, and the Middle East. Small-scale producers are in South America, Kenya, and South Africa. Require transportation to site as not widely available.	The material and manufacturing costs are high and there are limited manufacturers of eco-bricks worldwide. Bricks range anywhere from USD 7.70/brick (Kenya) to USD 17.55/brick (USA). As manufacturers are limited, associated transport costs would be relatively high. Labor/installation costs would	Compressive strength of recycled plastic bricks is4.93 MPa (14.6% higher than conventional concrete bricks), relative to the standard hollow concrete block strength of 3.5 MPa. Risk of chemicals leaking into the surrounding environment needs to be further evaluated.	Yes – plastic bricks can be mass manufactured. Has potential applicability in other sectors and for other purposes, and increased scale and use cases may increase availability

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					be minimal as most eco-bricks function the same as standard bricks.		in local markets and reduce cost.
Gabion	No	Lateral load-bearing structures for retaining walls and semi-below ground uses for earth-retaining structures (geogrid reinforcement) as well as above grade uses, channel and streambed coating (erosion control), hydraulic works in emergency situation, landscape aesthetics. Used worldwide.	Rectangular cages made of zinc-coated steel wire mesh and filled with stone. Material to be used as a lining where individual units are stacked and tied together with fasteners. They have been used for retaining walls above and below the ground surface.	Widely available in the US, Europe, Southeast Asia (Indonesia and the Philippines), India, and parts of Africa (South Africa and Kenya). Likely available in urban areas worldwide and anywhere with access to supply chains for the materials needed.	Depending on the context and availability, gabion price ranges from as low as USD 1 per m^2 to USD 30/m^2 for standard gabion and up to USD 100/m^2 for higher-quality material. Using recycled fill material reduces fill costs if locally sourced. Transport costs are not readily available and are regionally variable. Time and labor intensive, as gabions are filled with stone and manually tied together.	Zinc-coated wire mesh has a lifespan of about 50-60 years (Maccaferi), and a useful life of 100 years. When used as a retaining wall, the strength of the wall is dependent on the soil type, fill type, and ratio of the wall height to base length. As a result, these walls are able to withstand typical lateral soil pressure from soil 8-21 kN/m^3.	Yes – gabion has potential to use affordable and widely available materials to create structures that are commonly used for similar applications (retaining earth).
Rebar-reinforced fabric lining	Yes. A prototype was tested in Ghana by World Vision and Messiah University.	Has sufficient proof of concept for use as latrine pit lining.	Fabric used as the liner, kept in place with rebar and wire mesh placed along the circumference of the pit. This was tested with World Vision and Messiah University and has been examined by the Centre for Affordable Water and Sanitation Technology and others in the water, sanitation, and hygiene (WASH) sector.	Materials are generally available in areas with access to supply chains.	Rebar reinforced lining cost ranges from USD 26-40 to construct the entire structure. Rebar contributes to most of the cost (60%). Transport costs are not readily available but given the likely availability of the source materials for other purposes, these costs would be relatively low in urban areas or areas with access to supply chains.	Originally tested to provide a solution to pit collapse with sandy soils. Longevity and durability assumed to be limited due to the nature of the fabric. Depending on the fabric used, risk of chemicals leaking into the surrounding environment needs to be further evaluated.	Maybe – rebar-reinforced fabric lining has potential to be used at a larger scale than it currently is, but additional research on ideal fabrics/materials and longevity is needed.
Hempcrete/ hemp concrete	No	Not load-bearing and no below-ground proof of concept. Used in construction for internal and external insulation. As a new material that is expensive, it is mostly used in higher-end construction in high-income countries.	Hemp is a strong natural fiber and is used as a concrete substitute called hempcrete where it can be formed into blocks similar to a concrete block and bound together with a lime-based binder. There is potential for it to be used as a concrete block substitute for pit lining.	Hempcrete is available in the US, Europe, and South America. There are also some manufacturers in South Africa, but it is not widely manufactured worldwide. Hemp is grown in Asia, Africa, and South America. It is legal and grown in 11 African countries (Botswana, the Kingdom of eSwatini, Ghana, Lesotho, Malawi, Morocco, Rwanda, South Africa, Uganda, Zambia, and Zimbabwe), but it may face legal challenges in much of the region. Hemp is more widely grown and accepted in the marketplace in Asia.	Hempcrete blocks 8 in (203 mm) x 16 in (406 mm) (equal to that of standard hollow concrete blocks) cost USD 17/block. Not available worldwide so transport costs would be high if not manufactured on-site, and labor/installation costs would be comparable to those for standard brick/block lining installations.	High capacity to retain water, which can cause swelling and bio-decay of the material, as well as poor mechanical performance. Highly porous causing a poor adhesion to the lime binder that results in an elastic-like behavior. Requires additional research and testing for below grade use due to these factors. Lifespan of hempcrete walls to be around 100 years with hardness and rigidity increasing over time (note this is above grade and unsaturated). Compressive strength of 1.13 MPa (much less than the average	No - manufacturing, sourcing, and legal challenges currently limit the ability to further test and research hempcrete's potential, and its limited compressive strength and water-retaining nature will limit its effectiveness for most pit lining applications.

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						strength of a concrete hollow brick, 3.5MPa). Strength can be increased by increasing the amount of binder used.	
Concrete cloth	No	Load-bearing proof of concept and is commonly used to retain soil and reinforce structures (beams, pilings). There is limited proof of concept for below-ground uses. Above grade uses as tents for emergency housing, slope protection, structure reinforcement and repair, ditch, channel, berm and culvert lining.	Concrete cloth comes as a roll or sheet and is laid on the appropriate area, fastened with nails/screws/fasteners and secured with cement on the overlapped areas. It rolls out like a roll of fabric and then, once fastened, is saturated with water, causing it to harden into a concrete shell. There is potential to use this as a pit liner, however no proof of fully vertical use is available.	Available worldwide, specifically in the US, Europe, Africa (South Africa, Kenya), and Central and Southeast Asia (India, China, Indonesia, Malaysia, and the Philippines). Likely available in other major cities worldwide in areas connected to supply chains. Likely less available in parts of Africa, particularly rural areas with minimal concrete road and other civil construction.	Concrete cloth is widely manufactured on an industrial scale and ranges from USD 50–100 per m^2. Transport costs are not readily available and are region dependent. However, it is widely available so these costs would be relatively low in urban areas or areas with access to supply chains. The product is compact compared to its coverage area, thus transport costs would be small compared to product size. Installation of concrete is straightforward but does require knowledge/skill set as it is not a typical material such as brick and may require prior experience with the material for installation and thus more skilled workers.	Concrete cloth is available in the market in rolls. Concrete cloth is typically applied horizontally or on a slope, but not fully vertical as for pit latrines. 100-year lifespan reported for concrete cloth. Compressive strength of 35-60 MPa. Comparable to that of standard concrete.	Maybe – concrete cloth may be suitable to urban and peri-urban areas where roadways, culverts, and other infrastructure would also warrant its use. Otherwise, it will be difficult for this material to achieve scale in most rural markets. It is also currently cost-prohibitive.
Stabilized soil blocks (SSBs)	No	Load-bearing and used below ground when cement is included in brick manufacturing and moisture barrier applied. Used above ground for construction of structures and buildings worldwide. Used below ground for basement construction. "Mudlblock" lining reported for use in latrines in Nigeria (WaterAid), where similar to SSBs, mudblocks are compact earth blocks that are then stacked, in this case for pit linings.	Material to be used as a substitute for concrete bricks in latrine pit lining. SSBs (tested in Sudan) are building blocks made from ordinary soil mixed with little cement, little water and then highly compacted in a block press, resulting in a very solid, dense, and low-cost building block. Ideally reduces the number of trees cut down in areas to use with wood fire kilns. Used for above-grade structures of latrines.	Not manufactured on a large scale, but often manufactured locally or on-site. Requires a specialized machine to press the bricks, creating a barrier to widespread use. They have been manufactured in communities in Sudan where UN Habitat brought the machines in and trained workers on how to use them. Limited evidence elsewhere of their use.	SSBs cost USD 0.36 per 29x14x12cm block in Sudan. They are not industrially manufactured and usually manufactured on-site. This cost is dependent on material availability and availability of an SSB machine, which may increase cost. Material transport costs are minimal when manufactured on-site. Training is required on how to produce the blocks (how to use the machinery as well as what soils are best) and curing the blocks is also very labor intensive. However, the blocks function as standard bricks and thus require low skilled labor and have comparable installation costs.	Strong SSBs are produced from soils with high sand content. Overall time and labor intensive as they are manufactured by hand and the curing process is lengthy. Compressive strength of 4-7 MPa. Prone to cracking and saturation under wet conditions and low resistance to water penetration, resulting in crumbling and structural failure. High shrinkage/swelling ratio, resulting in major structural cracks when exposed to changing weather conditions. WaterAid recommends that "mudblocks" not be used when a pit is subject to	No – SSBs are labor intensive and demonstrate little market potential. Similar types of equipment and material needs likely mean this material will not reduce costs in comparison to standard brick-making practices.

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						standing water (WaterAid). These effects on SSBs can be avoided with the inclusion of cement in the brick mixture when manufactured and the application of a moisture barrier before construction.	
Cement Reinforced Stabilized Soil	Yes. CAWST piloted this pit lining method in Liberia.	Proof of latrine pit lining	Soil excavated from the dug pit is combined with cement and a small amount of water. A mold is then placed in the pit that leaves a gap between the edge of the pit and the mold. The mixture is then filled into this space in layers until a lining is complete.	Created on site with soil from the dug pit and cement, thus widely available where cement can be sourced. Requires a circular mold which may be hard to source/ create depending on metal/ general material availability.	Cement is widely available and has low transportation costs. There may be higher material costs for the mold materials (plastic, metal etc.). Labor/installation costs are low as it does not require skilled workers.	Applicable where the water table is below the pit and generally in dry pits with relatively stable soil.	Yes- this method utilizes local resources, does not require skilled labor and is therefore a cost effective pit lining method that should be further explored.
Wood/ bamboo	Yes. Wood and bamboo are often employed for pit lining as a low-cost option, often implemented as a woven structure. Proof of lining in Nigeria (WaterAid).	Proof of latrine pit lining use.	Woven bamboo or wood lines the inside of a pit. WaterAid has published a briefing note that highlighted the use of bamboo as lining.	Regionally dependent on bamboo and wood availability. This method is often used by those in more rural areas with access to natural resources.	There are limited material and transportation costs as this method is used when materials are available locally. Wood/bamboo are typically woven for lining use and thus do require skilled workers to complete this potentially leading to higher installation costs. If a community possessed this skill, it may serve as a potential income-generating activity. If cement is used as a mortar-like material to bind the lining, a small cost is incurred.	Requires a different skillset than that of typical construction materials (such as for laying bricks). Natural materials may degrade quickly and have high water absorption abilities. Based on anecdotal evidence, a woven design can help increase durability, and these lining materials are often implemented with a thin layer of packed earth, cement, or a similar binding material. The addition of resins in conjunction with bamboo may increase durability.	Yes – there are a wide range of installation methods and practices for using wood and bamboo for pit lining, which should be further explored. They are widely available in most areas, and their use in combination with coatings, sealants, and binders also warrants further research.
Sandbags	Yes. Used in refugee camps in Kenya and Sudan implemented by United Nations High Commissioner for Refugees. No reports regarding resistance to collapse or longevity. Also	Proof of latrine pit lining use.	Stacked burlap or woven polypropylene sandbags line the inside of a latrine pit. Polypropylene sandbags are preferred for pit lining due to durability and resistance to elements. In Kenya and Sudan, they were found to be more stable than oil drum linings.	Sandbags are often available worldwide in areas connected to supply chains with access to other construction materials. Unfilled, they are lightweight and suitable for places with transport challenges.	Sandbags cost anywhere from USD 0.25–0.50/bag without fill. If the fill is sourced on-site from the excavated pit, the total sandbag linings can cost around USD 30. Overall, the costs of sandbags have been found to be up to 40% cheaper than the cost of bricks over the same area. Transport costs are minimal when the sandbag fill is found on-site from the excavated pit and labor/installation costs are low	Installation of sandbag liners can be labor intensive due to the weight of the sandbags, though the design and assembly itself is simple. Lifespan unknown, although the pits in Kenya reported a 2-year fill rate. Tests run by World Vision indicated significant resistance to soil pressure. Out of 800 liners that were tested, none collapsed. Depending on the sandbag material, risk of	Yes – sandbags have primarily been used in humanitarian contexts but hold potential for many rural areas as well.

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	studied by Messiah University and World Vision for use as an affordable pit lining option.				as low skilled workers can construct with this method.	chemicals leaking into the surrounding environment needs to be further evaluated.	
Dry concrete rings (iDE Easy Latrine)	Yes. Installed as part of the Easy Latrine in Cambodia (400,000 Easy Latrines delivered to date, no information on breakdown of dry vs. wet ring design)	Proof of latrine pit lining use.	Concrete lining, typically implemented in 3-ring stacked design.	Same as standard concrete manufacturing, with a higher content of gravel and large aggregate to increase porosity and infiltration. Dry rings are faster to manufacture than wet rings. These break more easily than wet rings/standard concrete rings and the weight of concrete rings generally adds to transport challenges/cost.	3 rings cost approximately USD 12 in 2009 and there is no significant cost difference between dry and wet rings. Transport costs are region and context dependent and labor/installation costs are comparable to other concrete rings.	Dry rings not ideal for areas where the water table rises. Can break more easily during transport, but no references to issues/collapse once installed underground.	Maybe - proof of concept and supply chains exist in some contexts. Some concerns linked to transport and applicability in different soils, which further research should seek to unpack. The design and implementation have been tailored and fit to the Cambodian context, and this solution is unlikely to address challenges faced in many African contexts.
Wet concrete rings (iDE Easy Latrine)	Yes. Installed as part of the Easy Latrine in Cambodia (400,000 Easy Latrines delivered to date, no information on breakdown of dry vs. wet ring design)	Proof of latrine pit lining use.	Concrete lining, typically implemented in 3-ring stacked design.	Same as standard concrete manufacturing, though designed to be nearly impermeable, and thus are larger to accommodate fill rates. Wet rings are slower to manufacture than dry rings. Wet rings sometimes have holders added to increase perforation, using PVC pipes that are removed once the rings dry. Break less easily than the dry ring design. Weight of concrete rings generally adds to transport challenges/cost.	3 rings cost approximately USD 12 in 2009 and there is no significant cost difference between dry and wet rings. Transport costs are region and context dependent and labor/installation costs are comparable to other concrete rings.	Wet rings are good for flood-prone areas, and often implemented as part of a sky latrine, where the latrine structure is built on stilts with pipes that run to the ground. There can be challenges flushing sky latrines in clay soil types. No references to issues/collapse once installed underground.	Maybe - proof of concept and supply chains exist in some contexts. Some concerns linked to transport and applicability in different soils, which further research should seek to unpack. The design and implementation have been tailored and fit to the Cambodian context and this solution is unlikely to address challenges faced in many African contexts.

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Natural resins	No	Primarily used in residential construction as a flooring material or for road pavement. Examples include EarthEnable, K31-APS, and AggreBind.	Resin/coating. Stabilizes earth (soil/clay) to improve compressive strength and, in some cases, make the earth more water-resistant. Provides an alternative to bricks/blocks and concrete.	Resin itself is only currently widely available in North America or Europe. EarthEnable operates primarily in Rwanda and utilizes natural resins there on a small scale. There is potential to produce the resins locally, though limited cases have been found in African or Asian contexts. The binder is simply added to readily available soil and aggregate (up to 4 liters of resin per cubic meter of bricks/blocks produced) or applied to the surface of a material to act as a sealant. Similar to those for bricks/blocks unless produced on-site, though resins will need to be imported if not manufactured on-site. Note that resins can be quite complex to produce.	Natural resins typically cost USD 5–10 per liter. Transport costs are low as the product volume is small compared to coverage area. Natural resins function similar to unnatural resins that are more commonly used for sealing bricks/blocks function in typical construction. Thus this may be standard practice and well-known to local masons.	Applied with the same method as typical binders used in construction (cement) or sealant (silicone/latex) acting as a water barrier to those for bricks/blocks or cement, which may be standard practice and well-known to local masons. Some natural resins/coatings may not be compatible with organic matter in the soil. Examples of installed floors and roads can last between 10-20 years, and many natural resins have a shelf life of up to 2 years. Fairly high compressive strength (up to 12 MPa). Long drying time of up to 4 weeks (EarthEnable).	Yes – natural resins may have manufacturing limitations and availability concerns, but their use in combination with many existing materials used for pit lining holds promise for increasing durability at a relatively low price point.
Xanthan gum (soil stabilizer) and biopolymers	No	Proposed in current research as an alternative soil stabilizer to traditional additives such as lime and cement. May have applications to pit lining by improving soil properties around the pit.	Soil stabilizer. Improves the compressive and sheer strength of clay soils due to electrostatic bonds that form between xanthan gum and clay particles. May increase clay soil strength and minimize need for additional lining materials.	Readily available from food additive stores, which are likely concentrated in urban areas and rural towns/growth centers. Otherwise difficult to manufacture. The stabilizer is simply added to soil at a concentration of ~5% or less by dry weight of the soil. Material itself is needed in fairly small quantities	Xanthan gum costs USD 13/kg, and transport costs are low as the product volume is small compared to coverage area. Exact installation methods not yet defined and thus labor/installation costs are unknown.	Exact installation methods not yet defined. Works best in soils with a high clay content. Research on this is primarily focused in Asia. Has the most potential in areas where it can be purchased in the marketplace. Compressive strength of up to 0.083 Mpa.	Yes – soil stabilizers should be examined and field tested for their potential to reduce the need for lining, or to be coupled with cheaper (but less strong) lining materials. Xantham gum is widely available.
Gypsum	No	Gypsum blocks have been used in construction for over 100 years, though often used in modern times for indoor walls and partitions. Gypsum blocks have historically not been as commonly used for load-bearing walls and structures.	Alternative to concrete. Gypsum is a mineral commonly used in drywall and has been used as an alternative to concrete for wall and flooring construction. High-density gypsum has been used to construct entire homes (Amatec) and may be stronger than concrete in many applications.	Some technologies (e.g., high-density gypsum) are currently manufactured in North America, but through a replicable process than can be done with minimal energy requirements. Otherwise, gypsum is readily available in many cities and rural growth centers and can be packed with agro-waste such as rice straw to create brick alternatives. Material is very	Gypsum costs around USD 40 per ton (Amatec) and if used as a concrete alternative is relatively cheaper than concrete to transport due to its lightweight nature. Construction using gypsum blocks would be stacked in construction similar to bricks or concrete blocks.	Requires up to 30 minutes to harden, but otherwise straightforward to install. Similar to concrete, so would likely be installed in similar ways (e.g., stackable rings). Compressive strength of 50-100 Mpa (Amatec). Gypsum is generally not moisture resistant, and it is unclear if high-density gypsum addresses this concern.	Maybe – high-density gypsum has potential to drastically reduce transport costs and challenges associated with concrete construction, and there are many other construction applications that may help increase

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				lightweight and thus easy to transport. Manufacturing may be able to happen on-site.			its available in the market and reduce cost. Limited manufacturing options currently, primarily in high-income countries. A lack of water/moisture-resistant options renders this an unlikely current solution for lining.
Rocks/stacked stones	Yes. There are examples of stacked stones for pit linings all over the world, primarily in places where suitable rock is abundantly available.	Proof of latrine pit lining use.	Natural material that can stack similar to bricks/blocks to form pit linings. Often stacked dry (no mortar) but can have voids filled with smaller rocks/aggregate and often have thin layers of concrete poured over the top.	Specifically used in areas with locally available stone/rock.	There are limited material and transportation costs as this method is used when materials are available locally and material and transportation costs will only accrue when the materials are not available or if additional materials (like cement binder or coating) are used. Also do not typically require special training.	As discussed during interviews, a 3-meter-deep pit takes approximately one day to line. While little published evidence exists on longevity, there is anecdotal evidence in Uganda of stacked stone pit linings lasting for over 20 years.	Maybe – this material is widely used in many contexts with suitable rock available, but little experience and evidence have been published on its success and important considerations for construction.
Rubber tires (recycled/ used)	Yes, used for [pit and trench latrines]().	Proof of latrine pit lining use.	Recycled tires used to line the pit	Availability dependent on region as sourced locally due to recycled material.	There are minimal to no material costs as tires are recycled and would be sourced locally. Function similarly to standard bricks and thus require low skilled labor and have low installation costs.	Requires access to old/ recycled tires. If installed in areas with a high water table or frequent flooding, tires will float. Limited data on the longevity of pit linings constructed with tires, though the narrow pit diameter may result in quick fill rates. Limited data on the durability of pit linings constructed with tires. Risk of chemicals leaking into the surrounding environment needs to be further evaluated.	No – repurposed materials hold little potential for widespread scale and adoption and pose pit effectiveness constraints and environmental contamination concerns.
Oil drums (recycled/ used)	Yes. Many reports and manuals state that oil drums are an option for pit linings; however, there	Proof of latrine pit lining use.	Recycled oil drums used to line the pits. Typically, two are used and holes can be drilled to create a perforated lining.	Availability dependent on region as sourced locally due to recycled material.	There are minimal to no material costs as oil drums are recycled and would be sourced locally. Minimal installation costs as two drums are simply placed in an excavated pit.	Requires access to old/recycled oil drums. Requires two drums, one placed on top of another in an excavated pit and fastened together. Anecdotal evidence suggests	No – repurposed materials hold little potential for widespread scale and adoption and pose pit effectiveness

Material	Proof of concept for pit lining?	Typical applications/use cases	Material type/additional details	Availability *Material sourcing, manufacturing, and transportation needs*	Affordability *Material, manufacturing, transport, and labor/ installation costs*	Applicability *Installation and contextual requirements, longevity, and durability*	Recommended for further research and testing?
	is no published evidence of its use. Use in Kenya reported on.					3–4-month lifetime. Risk of chemicals and other contaminants leaking into the surrounding environment needs to be further evaluated.	constraints and environmental contamination concerns.
Ferrocement	No	Commonly used to construct water tanks and above-ground toilet structures.	Material to be used as a lining alternative. It is a combination of cement and wire mesh (provides tensile strength), where the wire mesh (chicken wire) is molded to the desired shape and then a light cement layer is applied over it.	Both cement and wire mesh are widely manufactured and expected to be available in most urban areas connected to supply chains. However, it may be more difficult to source for rural areas.	May cost approximately $150 per cubic meter of materials. The transport costs are minimal as both the mesh and ferrocement are light when transported to the location either installation-ready or for on-site manufacturing. Labor/installation costs are minimal as it does not require skilled workers.	A good latrine lining option in more rural areas as limited resources are needed to construct it (water, cement, sand, and wire mesh). Compressive strength of 28-69 Mpa. Improper manufacturing can lead to rusting of reinforcement, reducing the life of the structure.	Yes – ferrocement has potential to reduce concrete needs (reducing cost), and materials such as wire mesh are widely available in many rural markets. Ferrocement is commonly used for other applications as well, so consumes and masons may be familiar with using it.
LIXIL SATO plastic liner	Yes (through field testing - no widespread implementation yet)	Proof of latrine pit lining use.	Plastic perforated panels that snap together to form a lining (leach pit equivalent)	Would need to be shipped to most locations currently. Testing has focused on Malawi, Uganda, and India to date. Aside from the need to be imported, the plastic lining is lightweight and suitable for places with transport challenges.	USD 65-75 for a set of 18 plastic panels for pit lining. Transport costs to site are significantly lower than for bricks or concrete due to lightweight and compact nature. The liner cannot be manufactured on-site, but installation is straightforward and would take far less time than a cement or brick design, as the plastic panels simply snap together before inserting into the pit.	Likely best suited for wet sanitation applications (likely to be sold alongside the SATO pan), but also suitable for areas with challenging terrain/transport challenges. Designs for flood-prone areas underway. Most recent prototypes hold up well to field tests, maintaining their shape with minimal to no deformation. Very durable hard plastic with little to no risk of collapse.	Yes – this has potential to be implemented in a wide range of contexts and sold/scaled similarly to the SATO pan.
Digni-Loo	Yes, over 30,000 installed in Ghana.	Proof of latrine pit lining use.	Entire latrine product, featuring a lining to reinforce pits in areas with collapsible soils. No superstructure included.	Would need to be shipped to most locations. Testing and implementation focused on Ghana. Lightweight but bulky to transport, which may increase costs for some households if scaled more widely.	USD 81 for the lining and slab. Transport costs are lower than for bricks or concrete due to lightweight nature. The Digni-Loo cannot be manufactured on-site, but installation is straightforward and the pieces can be fitted together easily.	Well-suited to wet sanitation applications, but also suitable for dry sanitation. Capacity of the pit may be limited due to fixed size options of the lining. Very durable.	Yes – the potential for this to be implemented outside of Ghana warrants additional research, as well as better understanding of consumer preferences.

APPENDIX B: PIT LINING EXPERIENCES ACROSS CONTEXTS

Appendix B provides examples of pit lining materials, methods, and experiences across a wide range of contexts in Asia and Africa. Most of these experiences emerged through stakeholder interviews and additional follow-up, with some additional examples identified through the desk review process. This list is not exhaustive but is meant to provide additional details on implementation options and evidence to support the findings and recommendations presented in the report.

SOUTH AND SOUTHEAST ASIA

Bangladesh

In Northern Bangladesh, a government push for latrine rings resulted in lined pits being a sign of prestige among consumers.[6] The government standard is a cement 3-ring design with narrow gaps for leaching. Northern Bangladesh has more stable soils and generally sees deeper pits being dug (20 feet deep). Because southern Bangladesh generally sees more poorly designed pits, iDE has worked with stakeholders to improve pit design and prevent collapse. In southern Bangladesh, brackish groundwater degrades cement and sandier soils commonly result in pit collapse. A mesh lining made from fishnets was and is still being implemented in Bangladesh, with initial results showing a positive impact by reducing fill rates. No additional learning from this innovation has been widely shared or published to date. From a materials perspective, there is minimal gravel in Bangladesh to work with. Due to the high number of brick manufacturers in-country, however, it may be cheap and easy to implement brick honeycomb designs where local conditions support it.[7]

Bhutan

Rocks are used for lining pits in many parts of Bhutan with collapsible soils but an abundance of locally available, stackable rocks. There is anecdotal evidence that this reduces fill rates due to the larger voids between the rocks allowing for increased permeability.[8]

Cambodia

iDE has experimented with adding lime to their concrete blocks to increase durability in resistance to high levels of rain and inundation, as well as adding lime to full pits to assist with pathogen neutralization.[9] Overall, two primary lining designs are implemented by iDE in Cambodia: dry concrete rings that use a permeable mix (e.g., more gravel) to increase leeching into the surrounding environment, and wet concrete rings that are impermeable.[10] The dry concrete rings face some challenges with breakage during transport. Wet concrete rings are designed with a larger diameter to address their quicker fill rates (due to a fully sealed design). Both are designed for wet pit applications and to fill in approximately 2–3 years. For both dry and wet concrete rings, iDE receives more complaints from households about high fill rates in areas with clay soils and flood-prone areas. Occasionally, holes are added to the wet rings by inserting PVC pipes prior to drying, which are then later removed. iDE is exploring the use of plastic container-based sanitation for flood-prone areas, but

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they have concerns about durability and longevity. As of the writing of this report, this is in early stages of development and has not yet been implemented or field-tested.

In the past, iDE has also experimented with concrete linings that were thinner but equally strong to address material costs. However, households continued to choose thicker linings due to perceptions of durability and overall effectiveness. Additionally, previous efforts to increase the porosity of concrete (for example, by adding rice husks to the aggregate mixture) have been met by consumer skepticism, with households often reverting to materials and designs they were most familiar with.

India

Across India, The FINISH Services Management Company trains masons on latrine pit lining construction using bricks and cement, noting the importance of sensitivity to contextual factors such as terrain and local soil properties. Pits are constructed to be sealed at the top to minimize the ability of floodwater flows into the pit and to ensure leaching does not happen too close to the surface. In these designs, leaching is often enabled through a brick honeycomb structure and junction chamber. However, in areas with high groundwater tables, pits are constructed to be fully sealed.[11]

The Government of India's norms (developed in 1957 with support from the World Health Organization) guide construction, and United Nations Children's Fund (UNICEF) supports FINISH's implementation of these norms. Examining toilets that masons had constructed in Bihar, FINISH noted the following deviations from best practice: masons did not construct a junction chamber; another pit could thus not be dug later and joined to it, reducing the time until emptying or abandonment; septic tanks were not connected to soak pits; footrests and pans were not aligned; lids of pits were of inferior quality; and a honeycomb lining structure was used all the way to the top of the pit.

Cement rings with drilled holes have been used in Odisha and Bengal. Clay rings have also been used and are much cheaper than cement/bricks but break easily. Pits in northeast India are sometimes constructed from bamboo that is painted with burned coal tar to minimize risk of corrosion.[12] This material has a reported lifespan of 5–6 years. Stone is also often used when locally available. In flood-prone areas, FINISH is experimenting with raised platforms and pits using plastic drums. The first phase of experimentation took place in Bihar, and a second phase will take place in Darbhanga.

WaterAid conducted a study in Tiruchirappalli, Tamil Nadu, finding that households and masons acted on a perception that liquids drain from the bottom of pits, resulting in pits constructed with solid-lined walls and a layer of sand at the bottom with no lining.[13]

Swachh Bharat provided a great example of a government-led initiative to promote sanitation but faced initial rigidity regarding design (enforcement of standard twin alternative offset pits lined with bricks in a honeycomb pattern). Much of this rigid design guidance persists today, favoring designs most similar to septic tanks, which are not appropriate for all implementation contexts.[14] The SATO pit liner is being piloted in India, with a cost of roughly USD 65–75 for a full set of 18 panels.[15]

Pacific Island Nations

In Pacific Island countries, oil drums, used tires, and rocks/coral have been used to line the sides of pits to prevent collapse. Coconut shells and coconut coir have also been used at the bottom of dry pits to

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promote aerobic conditions by separating the urine from the sludge. Used tires and oil drums have been used in the Solomon Islands for pit lining.

SUB-SAHARAN AFRICA

Ethiopia

In Oxfam's sanitation work in refugee camps, tiger worm toilets are often implemented. When liquids are unable to exit the pit into the surrounding soils, the worms drown, limiting their effectiveness for eating up the solids in the pit.

iDE in Ethiopia has prototyped pit lining solutions, including wood, used oil drums, used tires, and various cement-soil mixtures (WASHplus 2016).

Ghana

The Digni-Loo in Ghana is a plastic molded pit lining connected to a plastic slab (USAID 2017). The Digni-Loo is cited to take 1–5 years to fill and can last for up to 20 years under the most favorable conditions. To date, the Digni-Loo has reached a moderate level of scale in Ghana where 300,000 units were installed, with limited evidence of its applicability across a wide range of contexts.

Kenya

In coastal areas of Kenya with sandy soils, households have successfully used mud blocks commonly used for house construction for sanitation. This helped to address the collapse of unlined latrines during sudden rain events. Sand bags have been successfully used to line pits and provide structural integrity in emergency contexts in the arid parts of northern Kenya (Saxena & Den 2021). As in Uganda and other African countries, households will often dig pits as deep as they can afford to, as this reduces their need for future emptying and enables the pit to last longer.

Nigeria

Bamboo interwoven with flexible branches from local trees has been used for lining in some areas of Nigeria.[16] Scaling this material/method poses a challenge, as skilled artisans are required to implement specialized techniques for its use in subsurface sanitation. While the material itself is inexpensive, transport costs are significantly higher than the material cost, reducing market potential in areas where bamboo is not readily available. No durability issues have been identified due to rot in the areas where this lining has been implemented.

Senegal

The United States Agency for International Development (USAID) Assainissement – Changement de Comportement et Eau pour le Senegal (ACCES) program often faced challenges of high groundwater levels across sites. Lining was the default for all latrine construction regardless of soil stability and groundwater depth. However, lining was constructed to varying levels of thickness and permeability based on site conditions. Bricks and cement were most commonly used for lining, though mud blocks were used in a few contexts (Kedogou, for example) where they were already being constructed by masons and local artisans. The program experimented with a wide range of materials, with costs and associated consumer prices increasing with increased distance from Dakar. In areas with high

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groundwater levels, an additive called Sica was used in cement to make it impermeable. These pits were often sealed at the bottom, as well, to ensure they were watertight.[17]

Additionally, coconut shells are used in Senegal to support sludge treatment within pits. Essentially, a second pit was constructed for liquid to enter following drainage through the coconut filter. This provided a solution for odor control, but the impact on fill rates and other key criteria is yet unknown.

Uganda

Under the Uganda Sanitation for Health Activity (USHA), latrines were often constructed with collars at the top of the pit to reduce the risk of collapse.[18] While pits in Uganda are generally unlined, there are examples of lining where difficult conditions are known. In western Uganda, rocky terrain and collapsible soils are common. In this region, it is common to construct round pits lined with various sizes of rocks stacked together, with increased use of sand and cement near the very top. Anecdotal evidence suggests a lifespan of up to 20 years for these pits. Given that the rocks are available locally and households can contribute materials in-kind, the cost is significantly less than that of concrete. In the semi-arid regions of northern Uganda, there are examples of weaved basket-like linings lined with cement to improve durability while reducing cost by minimizing the amount of cement required. Little is known about the long-term durability of these linings.[19]

Ugandan government policy states that pits should be dug at least 15 feet (approximately 5 meters) deep, but consumers often prefer even deeper pits (often 30–40 feet/10–13 meters deep), as is the norm across much of sub-Saharan Africa.[20] In cities like Kampala where emptying services are employed, only the top of the pits are often emptied, leaving much of the contents behind.[21] The SATO pit liner is being piloted in Uganda, with a cost of roughly USD 65–75 for a full set of 18 panels.[22]

Zimbabwe

Linings have been constructed with stacked rocks and no mortar in Zimbabwe for a long time, but knowledge of this approach is fading. Master trainers are being developed across the country to implement construction practices associated with this design. The design allows for ample leaching into the surrounding soil. Where bricks are more commonly used in Zimbabwe, implementers struggle with quick fill rates due to poor leeching into the surrounding soil. PRO-WASH is currently examining a similar challenge across 23 woredas in Ethiopia, though no findings from this work have yet been widely shared or published.[23]

Zambia

USAID is interested in piloting the SATO pit liner to address challenges of pit collapse due to localized soil conditions. In this case, the SATO liner would provide additional structural stability for dry sanitation.[24]

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APPENDIX C: STAKEHOLDER INFORMATION

KEY INFORMANTS AND STAKEHOLDER ENGAGEMENT FOR PHASE 1			
STAKEHOLDER	**AFFILIATION**	**COUNTRIES REPRESENTED**	**PARTICIPATION**
Name(s) not shown	FINISH Society	India	KII, Stakeholder Consultation
Name(s) not shown	Water, Sanitation, and Hygiene Partnerships and Learning for Sustainability (WASHPaLS) #2	Global/Multiple	KII, Stakeholder Consultation
Name(s) not shown	WASHPaLS #2	Global/Multiple	KII
Name(s) not shown	USAID/ACCES	Senegal	KII, Stakeholder Consultation
Name(s) not shown	USAID/ACCES	Senegal	KII, Stakeholder Consultation
Name(s) not shown	UNC/UNICEF	Global/Multiple	KII
Name(s) not shown	Bill & Melinda Gates Foundation	Global/Multiple	KII
Name(s) not shown	Partners in Development	Global/Multiple	KII
Name(s) not shown	FINISH Society	India	KII
Name(s) not shown	iDE Cambodia	Cambodia	KII, Stakeholder Consultation
Name(s) not shown	iDE Cambodia	Cambodia	KII, Stakeholder Consultation
Name(s) not shown	Save the Children	Ethiopia, Zambia	KII, Stakeholder Consultation
Name(s) not shown	LIXIL	Global/Multiple	KII
Name(s) not shown	LIXIL	Global/Multiple	KII
Name(s) not shown	LIXIL	Global/Multiple	KII
Name(s) not shown	USAID/USHA	Uganda	KII
Name(s) not shown	UNC	Global/Multiple	KII
Name(s) not shown	UNC	Global/Multiple	KII, Stakeholder Consultation
Name(s) not shown	UNC	Global/Multiple	KII
Name(s) not shown	The Consortium for Decentralized Wastewater Management System Dissemination India	India	KII, Stakeholder Consultation
Name(s) not shown	Sied Sarl	Senegal	KII
Name(s) not shown	World Health Organization	Global/Multiple	KII, Stakeholder Consultation
Name(s) not shown	World Health Organization	Global/Multiple	KII, Stakeholder Consultation
Name(s) not shown	World Health Organization	Global/Multiple	KII
Name(s) not shown	Oxfam	Global/Multiple	KII, Stakeholder Consultation
Name(s) not shown	EarthEnable	Rwanda	KII, Stakeholder Consultation
Name(s) not shown	EarthEnable	Rwanda	KII
Name(s) not shown	EarthEnable	Rwanda	KII
Name(s) not shown	UNICEF	Global/Multiple	Stakeholder Consultation
Name(s) not shown	World Bank/London School of Hygiene and Tropical Medicine	Global/Multiple	Stakeholder Consultation
Name(s) not shown	Material Match Maker	Global/Multiple	KII

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